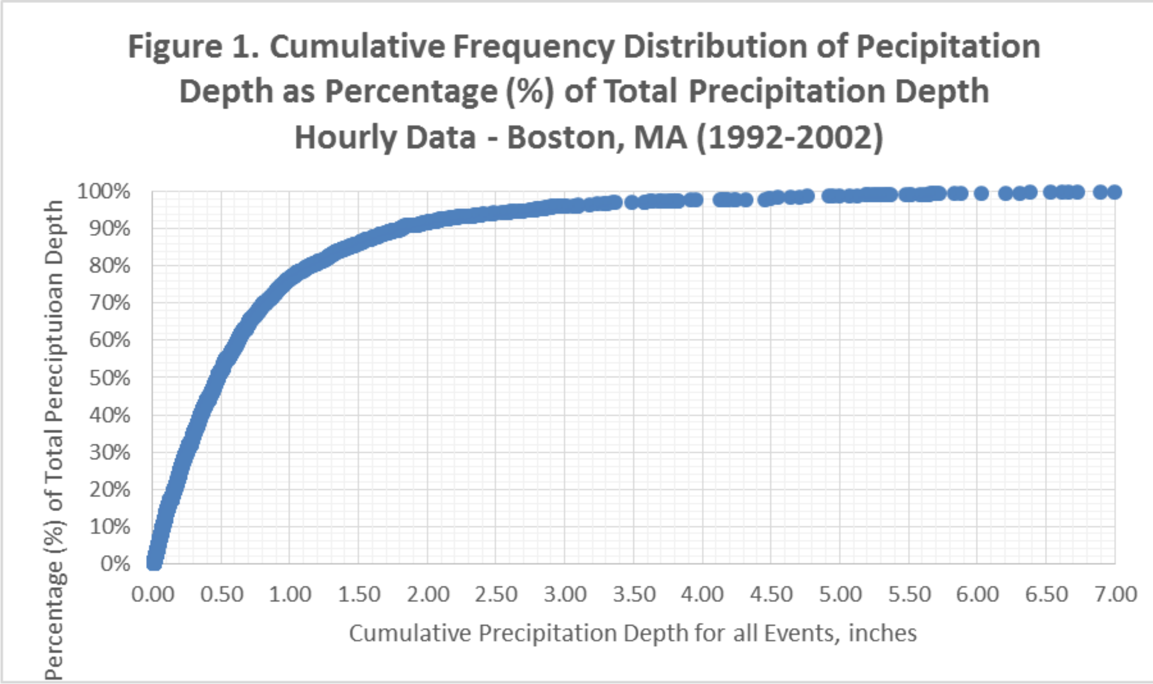
Analyses of Precipitation, Impervious Surface Runoff Depth, Storm Inter-Event Dry Period and Stormwater Nitrogen Load Delivery: Analyses were conducted to gain insight into the potential cumulative effectiveness of small sized stormwater controls designed to remove nitrogen in stormwater runoff from developed landscapes that are being considered as demonstration projects in Cape Cod, MA.

An analysis of hourly precipitation data and model generated runoff volumes for impervious cover was conducted using an eleven year record of hourly precipitation data for Boston, MA, 1992-2002. The precipitation data were analyzed to develop cumulative frequency distributions of: 1) event cumulative precipitation depths as a percentage of total precipitation depth for all events; 2) Event cumulative runoff depths as a percentage of total cumulative runoff depth for all events; and 3) Inter-Event Dry Periods (IDPs) for all precipitation events excluding precipitation events with depths less than or equal to 0.05 inches. This precipitation record was selected because it is the same dataset used in the development of the Region 1 BMP performance curves.

Continuous hydrologic model simulations of an impervious surface using the Storm Water Management Model (SWMM) was conducted using the same Boston, MA precipitation record, 1992-2002. Hourly runoff volumes were generated for an impervious surface for the 11 year record. Both precipitation data and runoff model output were used to summarize event data based on a minimum inter-event dry period of 6 hours without precipitation.

Lastly, an analysis of SW TN EMC data taken from the National Stormwater Quality Database (Pitt, 2008) was conducted to evaluate distributions of TN EMCs for various groupings of TN EMC data by event size: 1) precipitation event depths (e.g., 0 to 0.3 inches, 0.3 to 0.6 inches, 0.6 to 1.0 inches, …etc.); and 2) for all data less than or equal several precipitation depth thresholds (e.g., 0.25, 0.35, 0.45, 0.55, 0.65, … etc). Summary statistics of these data were used to together with the runoff volume analysis results to estimate percentage of the total TN load delivered as a function of runoff depth from impervious surfaces.

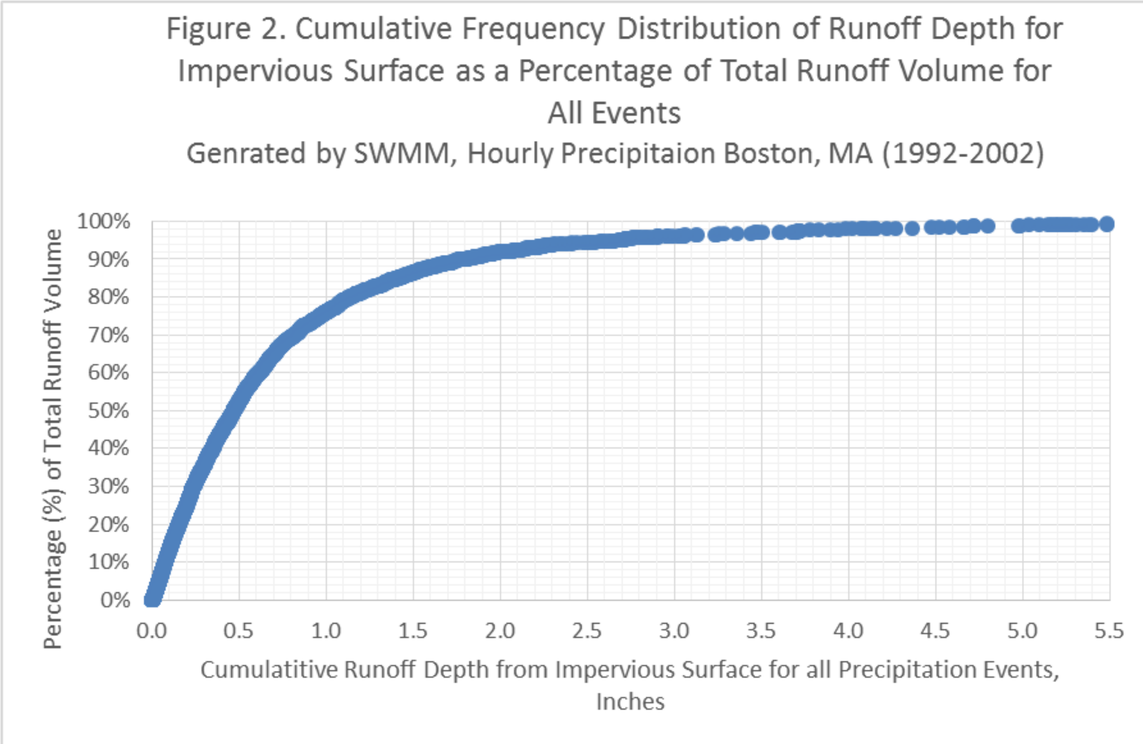
Precipitation Depth: Figure 1 presents the cumulative frequency distribution of precipitation depth as a percentage of the total precipitation depth for the complete record. For example, all storm events that have precipitation depths of 0.3 inches or less accounts for approximately 34.5% of the total rainfall. This value also includes the 0.3 inch portion of all events that have depths greater than 0.3 inches. This type of distribution is useful to gain insight into the cumulative amount of precipitation/runoff that would receive treatment by a control of a specified size. Using the same example as above it is evident that a control with a physical storage capacity to hold 0.3 inches of runoff depth from the contributing impervious area would provide treatment to approximately a third of the annual runoff volume. It is worth noting that not all precipitation generates runoff as some is captured in depression storage and some is lost to evaporation.



Runoff Depth: A slightly more refined approach to estimate the cumulative volume of runoff that would be treated by a control with a specific design capacity is to develop a cumulative frequency distribution of impervious surface runoff depth as a percentage of the total runoff depth generated for the period of record. In this case hourly runoff volumes from an impervious surface were generated using SWMM and the hourly precipitation data and daily temperature data for Boston, MA (1992-2002). In this case a depression storage of 0.05 inches was assumed. The corresponding cumulative frequency distribution is provided in Figure 2 and indicates very minor differences between the results shown in Figure 1 (0.3 inches runoff depth equals approximately 35.2 % of the total cumulative runoff for the entire record).

Inter-Event Dry Period: Retention time within the saturated low-oxygen reservoir of gravel wetland type systems is a key design feature for optimizing nitrogen removal. Typically, much of the retention time is accomplished between storm events. An analysis of inter-event dry periods was conducted to assess IDPs and the opportunities that will likely occur for providing sufficient retention times between storm events. Figure 3 displays the cumulative frequency distribution of inter-event dry periods between precipitation events for the Boston, MA 1192-2002 precipitation record. In this analysis all events of 0.05 inches or less were excluded because they are not likely to generate runoff.

James Houle of the UNHSC has indicated a 24 hour retention time is a minimum design target while a 30 hour time is optimal. Tables 1 and 2 provide summary statistics for IDPs and rainfall depths for all runoff events as well as for < 24 hours, ≥ 24 hours (Table 1); < 30 hours and ≥ 30 hours (Table 2). As indicated, the vast majority of rainfall events and total runoff depth have IDPs in excess of both 24 hours (75% of events and 82% of total precipitation depth) and 30 hours (71.3% of events and 78.5% of total precipitation depth).



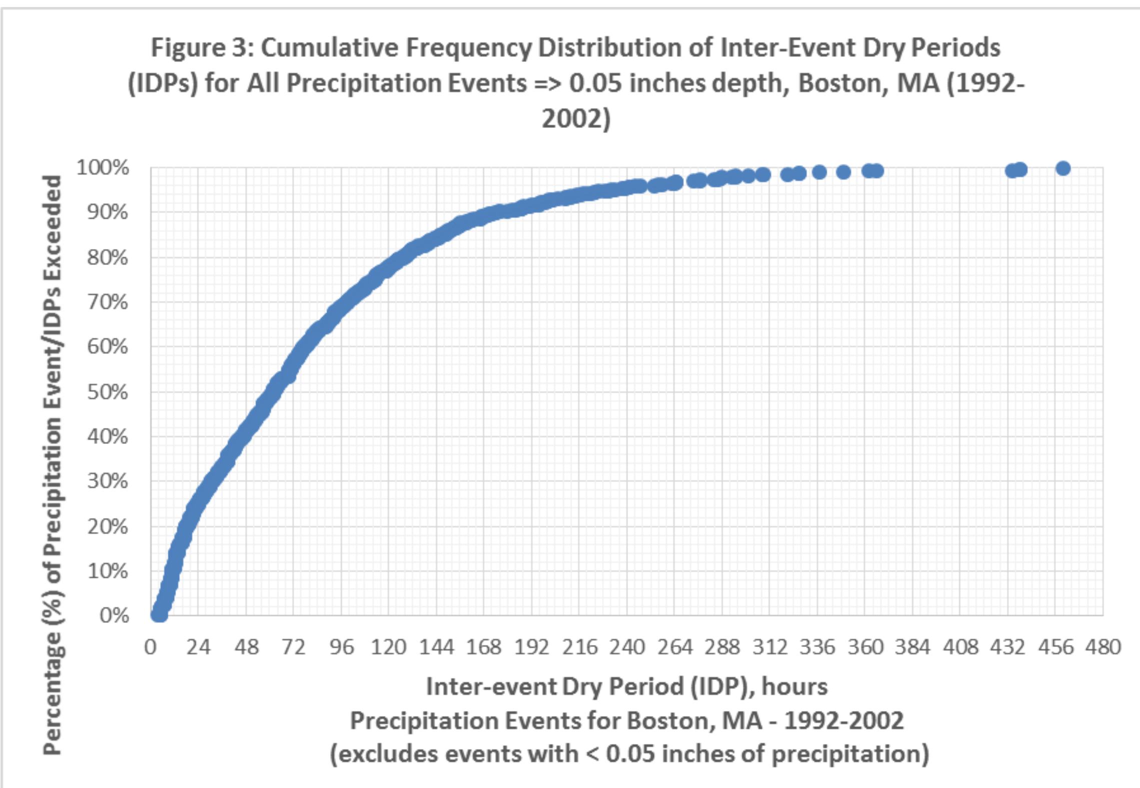


Table 1. Summary Statistics for Inter-Event Dry Periods (IDPs) and Precipitation Event Depths for Boston, MA (1992-2002) Including Events with IDPs < 24 hours and ≥ 24 hours -(Excludes precipitation events < 0.05 inches)

Dataset IDP	Total Number of Events	% of Total Events	Inter-Event Dry Period (IDP), hours				Total Precip. Depth, Inches	% of total Precip. depth	Event Precipitation Depth, Inches			
			Mean	Median	25th %	75th%			Mean	Median	25th %	75th %
All IDPs	863	100%	81.8	62.0	24.0	113.0	463.3	100%	0.54	0.31	0.13	0.69
IDP < 24 hours	213	24.7%	13.2	13.0	9.0	17.0	83.6	18%	0.39	0.24	0.12	0.50
IDP ≥ 24 hours	649	75.3%	104.4	82.0	52.5	131.0	379.3	82%	0.59	0.34	0.13	0.73

Table 2. Summary Statistics for Inter-Event Dry Periods (IDPs) and Event Depths for Boston, MA Precipitation Events (1992-2002) Including Events with IDPs < 30 hours and ≥ 30 hours - (Excludes precipitation events < 0.05 inches)

Dataset IDP	Total Number of Events	% of Total Events	Inter-Event Dry Period (IDP), hours				Total Precip. Depth, Inches	% of total Precip. depth	Event Precipitation Depth, Inches			
			Mean	Median	25th %	75th%			Mean	Median	25th %	75th %
All IDPs	863	100%	81.8	62.0	24.0	113.0	463.3	100%	0.54	0.31	0.13	0.69
IDP < 30 hours	248	28.7%	15.0	14.0	10.0	20.0	99.5	21.5%	0.39	0.24	0.12	0.50
IDP ≥ 30 hours	615	71.3%	108.7	87.0	57.0	135.0	363.9	78.5%	0.59	0.35	0.14	0.73

Stormwater Total Nitrogen (TN) EMC Data and Load Delivery Analysis: Nitrogen, and in particular dissolved inorganic nitrogen, is known to be highly mobile and susceptible for wash-off in early portions of storm runoff events from impervious surfaces. Stormwater TN EMC data from the NSQD for rainfall regions 1 and 2 were analyzed to gain insight into the distributions of EMCs based on rainfall depth. Data were analyzed for several storm size groupings for two land use groupings: (1) all residential; and (2) commercial/industrial/institutional. TN EMC data were divided into these two land use groupings because each group likely reflects very different drainage area conditions with respect to percent impervious cover in the drainage areas monitored. While the actual % imperviousness for each location are not available for the EMC data analyzed, residential drainages are typically between 15 and 40 % impervious cover, while drainage systems serving commercial/industrial /institutional land uses have typically between 55 and 85% impervious cover.

At this time, the Region is primarily interested in the characteristics of TN SW quality for runoff from areas that are entirely impervious because: 1) impervious surface generate far higher annual TN loads than pervious areas (see Table 3 below); 2) the runoff treated by small capacity BMPs will be comprised mostly of (if not all) impervious surface runoff since their capacities will be reached before pervious areas contributes runoff; and 3) for BMPs located in Cape Cod where most surficial soils are highly permeable sands, runoff from pervious areas will be non-existent for most storm events and only very small amounts for larger events. Table 4 shows the estimated depth of runoff from developed land pervious areas for varying precipitation depths and hydrologic soil groups (HSG).

Table 3: Proposed Average Annual Nitrogen Pollutant Load Export Rates for calibration of default HRU Time-series for use in Opti-Tool			
Nitrogen Source Category by Land Use	**Land Surface Cover**	**Runoff Nitrogen Load Export Rate, Kg/ha/yr**	**Comments**
Commercial (Com) Industrial (Ind) & Institutional	Directly connected impervious	16.9	WISE modeling by Geosyntec for the Squamscot River IMP, 2014. Avg of NLER for rooftops and other impervious surfaces for commercial and industrial
	Pervious	See* DevPERV	
Multi-Family (MFR) and High-Density Residential (HDR)	Directly connected impervious	15.8	WISE modeling by Geosyntec for the Squamscot River IMP, 2014. Avg of NLERs for rooftops and other impervious surfaces for residential
	Pervious	See* DevPERV	
Medium -Density Residential (MDR)	Directly connected impervious	15.8	WISE modeling by Geosyntec for the Squamscot River IMP, 2014. Avg of NLERs for rooftops and other impervious surfaces for residential
	Pervious	See* DevPERV	
Low Density Residential (LDR) - "Rural"	Directly connected impervious	15.8	WISE modeling by Geosyntec for the Squamscot River IMP, 2014. Avg of NLERs for rooftops and other impervious surfaces for residential
	Pervious	See* DevPERV	
Highway (HWY)	Directly connected impervious	11.4	WISE modeling by Geosyntec for the Squamscot River IMP, 2014. Avg of NLERs for roadways and freeway impervious surfaces
	Pervious	See* DevPERV	
Forest (For)	Directly connected impervious	12.7	WISE modeling by Geosyntec for the Squamscot River IMP, 2014. NLER for roadways
	Pervious	0.6	Derived from SWMM and P8 - Curve Number continuous simulation HRU modeling with assumed TN concentration of 0.8 mg/L for pervious runoff from forest lands. Median TN conc of 0.8 mg/l by (Budd and Meals, 1994)
Open Land (Open)	Directly connected impervious	12.7	WISE modeling by Geosyntec for the Squamscot River IMP, 2014. NLER for roadways
	Pervious	See* DevPERV	
Agriculture (Ag)	Directly connected impervious	12.7	WISE modeling by Geosyntec for the Squamscot River IMP, 2014. NLER for roadways
	Pervious	2.9	Derived from SWMM and P8 - Curve Number continuous simulation HRU modeling with assumed TN concentration of 2.5 mg/L for pervious runoff from agricultrue lands. Median TN conc of 2.5 mg/l by (Budd and Meals, 1994)
*Developed Land Pervious (DevPERV)- Hydrologic Soil Group A	Pervious	0.3	Derived from SWMM and P8 - Curve Number continuous simulation HRU modeling with assumed TN concentration of 2.0 mg/L for pervious runoff from developed lands. TN of 2.0 mg/L is based on TB-9 (CSN, 2011), and other PLER literature and assumes 50 % of unfertilized and 50% fertilized conditions.
*Developed Land Pervious (DevPERV)- Hydrologic Soil Group B	Pervious	1.3	
*Developed Land Pervious (DevPERV) - Hydrologic Soil Group C	Pervious	2.7	
*Developed Land Pervious (DevPERV) - Hydrologic Soil Group C/D	Pervious	3.4	
*Developed Land Pervious (DevPERV) - Hydrologic Soil Group D	Pervious	4.1	

Table 4: Developed Land Pervious Area Runoff Depths based on Precipitation depth and Hydrological Soil Groups					
Rainfall Depth, Inches	Runoff Depth, inches				
	Pervious HSG A	Pervious HSG B	Pervious HSG C	Pervious HSG C/D	Pervious HSG D
0.10	0.00	0.00	0.00	0.00	0.00
0.20	0.00	0.00	0.01	0.02	0.02
0.40	0.00	0.00	0.03	0.05	0.06
0.50	0.00	0.01	0.05	0.07	0.09
0.60	0.01	0.02	0.06	0.09	0.11
0.80	0.02	0.03	0.09	0.13	0.16
1.00	0.03	0.04	0.12	0.17	0.21
1.20	0.04	0.05	0.14	0.27	0.39
1.50	0.08	0.11	0.39	0.55	0.72
2.00	0.14	0.22	0.69	0.89	1.08
Notes: Runoff depths derived from combination of volumetric runoff coefficients from Table 5 of *Small Storm Hydrology and Why it is Important for the Design of Stormwater Control Practices*, (Pitt, 1999), and using the Stormwater Management Model (SWMM) in continuous model mode for hourly precipitation data for Boston, MA, 1998-2002.					

Figure 4 depicts how median TN EMC values vary based on storm group sizing for the two land use groupings. As indicated, the median values for the commercial group continues to drop as the storm size increases, while the median values for the residential group remain fairly constant for all storm size groupings greater than the 0 to 0.3 inch grouping (which is notably higher than the rest – 2.4 mg/L compared to ~1.8-1.9 mg/L). These results support the following important inferences and points:

1. Runoff events for small sized storm events, regardless of which land use group, have notably higher EMC than for larger storms which supports that inference that significant wash-off occurs during smaller storms and the early portions of larger storms. Additionally, it is reasonable to infer that the EMC data for the smaller storms are reflective of runoff that is primarily from impervious surfaces because the storm sizes are not of sufficient depth to generate notable runoff quantities from pervious areas;
2. The trend of declining median EMCs for the commercial group indicates that sources of TN that contribute to runoff decline as storm depths increase in size, while for the residential group there appears to be a consistent source of TN regardless of storm size. The difference in these patterns is most likely due to contribution of TN in runoff from pervious areas, which for the commercial group is likely to be much lower than for the residential group. While the EMC data for the commercial group are not representative of areas that are entirely impervious, these data are considered to be more reflective of impervious surface runoff quality than the residential EMC data.

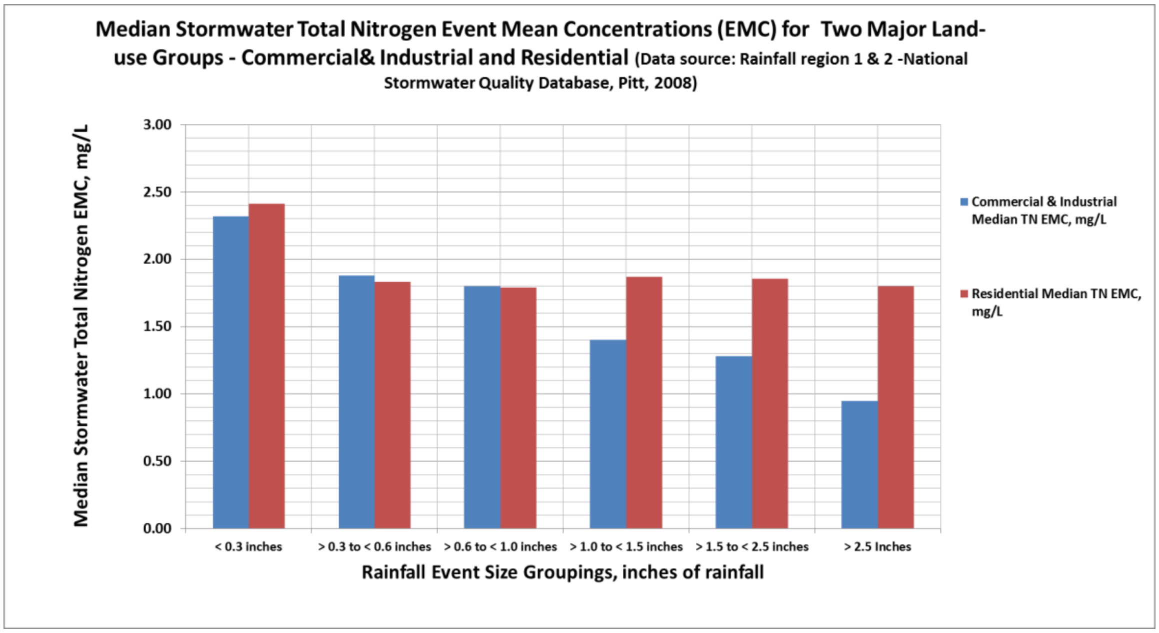
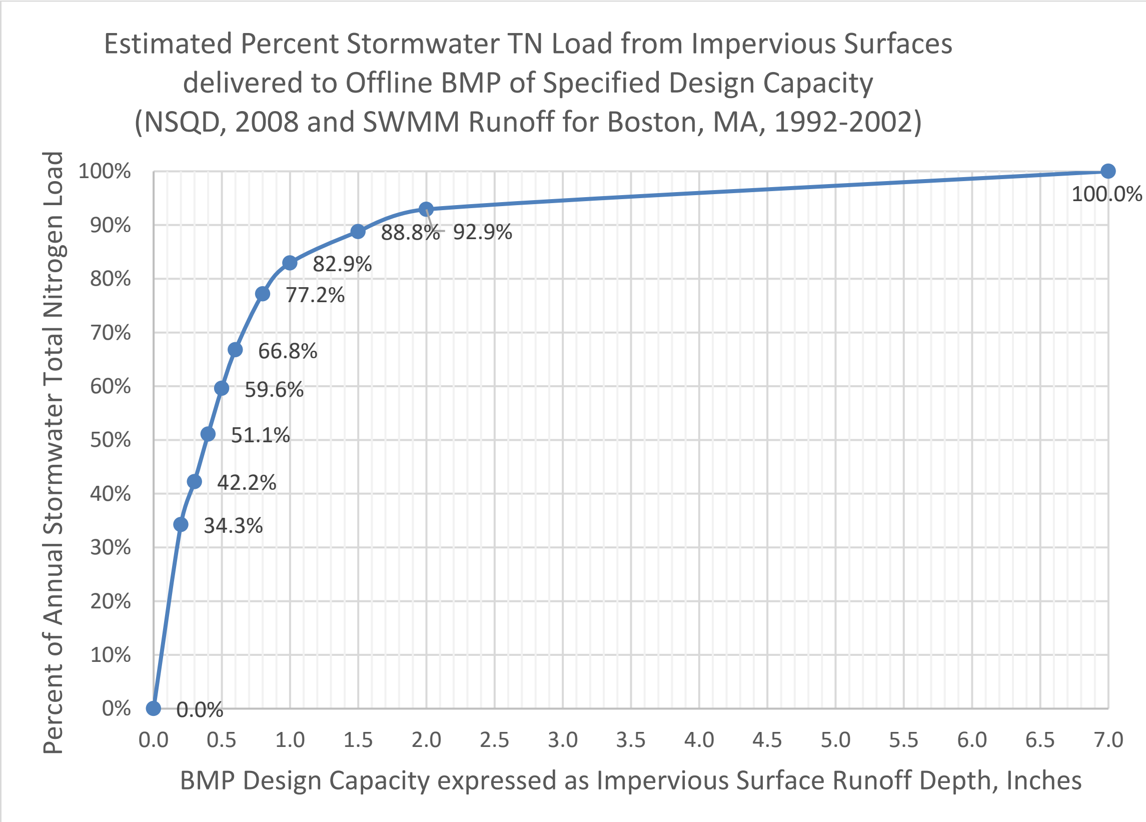


Figure 4: Median TN EMCs for Commercial/Industrial/Institution and Residential Land Uses based on Storm Event Depths

The delivery of TN load to BMPs based on design capacities expressed as impervious surface runoff depths have been estimated using the commercial median values of TN EMCs calculated for several rainfall depth thresholds, corresponding impervious surface runoff depths, and the cumulative frequency distribution of impervious surface runoff depth. These results are summarized in Table 5 and depicted in Figure 5. Corresponding runoff volume depths were assumed to be 0.05 inches less than the precipitation depth thresholds.

Table 5: Summary of TN Load Delivered based on Impervious Surface Runoff Depths for Commercial/Industrial/Institutional Land-Uses

Precipitation Event Depth Threshold, inches	Median TN EMC, mg/L	Corresponding Impervious Surface Runoff Depth, inches	Cumulative Depth of Runoff Delivered, %	Cumulative TN Load Delivered, %
<=0.25	2.46	<=0.2	25.6%	34.3%
<=0.35	2.16	<=0.3	36.0%	42.2%
<=0.45	2.10	<=0.4	44.8%	51.1%
<=0.55	2.08	<=0.5	52.7%	59.6%
<=0.65	2.07	<=0.6	59.5%	66.8%
<=0.85	2.05	<=0.8	69.5%	77.2%
<=1.05	2.01	<=1.0	76.1%	82.9%
<=1.55	1.89	<=1.5	86.4%	88.8%
<=2.05	1.86	<=2.0	91.9%	92.9%
<=7.15	1.84	<=7.1	100.0%	100.0%



Based on the results of this analysis an off-line BMP with the design physical storage capacity of 0.3 inches runoff depth from the contributing impervious surface would receive approximately 42% of the total annual TN load (~6.3 pounds TN per acre of impervious surface). As these estimates are based on the SW quality data for the commercial/industrial/institutional group it is likely that they do not entirely reflect the first flush effects on an impervious only surface and are likely to be under estimating the percentage of annual TN loads delivered to off-line small capacity BMPs from the contributing impervious surfaces.